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13. ABSTRACT (Maximum 200 words)

This work was focussed on the dynamics of stratified flow in sea straits, primarily the Bab al Mandab (BAM). Possible hydraulic control of the exchange flow in the BAM was investigated by analyzing data collected by Drs. Steve Murray and Bill Johns as part of a recent 2-year field program. The analysis centered on the calculation of long wave speeds for the first and second baroclinic modes of the stratified shear flows at the sill and narrowest section of the Strait. Doing so required advancements in the theory of internal long waves in straits with nonuniform cross-channel topography. The hydraulic character of the flow is vital in the understanding of the stratification in the BAM and in the neighboring Red Sea and Gulf of Aden. Theoretical studies of the effects of rotation on hydraulically controlled flows in straits were also carried out. The results reveal some remarkable structural features such as transverse hydraulic jumps, recirculations and splitting of the flow.

14. SUBJECT TERMS

Bab al Mandab, hydraulic control, critical flow, normal modes, stratified flow, waves, time-dependence

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Red Sea Studies
(final report)

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LONG-TERM GOAL

My long-term goal is to contribute to our understanding of the dynamics of the exchange flow through the Bab al Mandab and its effect on the general circulation and stratification of the neighboring Red Sea and Gulf of Aden.

OBJECTIVES

In this study, I sought to determine whether exchange flow through the Bab al Mandab is hydraulically controlled. In the event that control exists, I wanted to determine the locations of the control section(s) and hydraulic jump(s), the vertical structure (first or second internal mode) of the wave whose propagation is arrested at the control section(s), and the extent to which these factors are influenced by the earth's rotation. A second objective was to determine the effects of rotation and time-dependence on critical controls, hydraulic jumps, and other standard features of hydraulically-driven flows.

APPROACH

The approach has been to analyze direct velocity measurements made by Profs. Bill Johns (RSMAS) and Steve Murray (LSU) over the period June 1995-November 1996 at the Hanish Sill and Perim narrows of the Bab al Mandab. Initial efforts were centered on fitting the observed flow to a three-layer model but I have recently developed a continuously stratified model that takes cross-strait topography into consideration. This model avoids the ambiguities associated with defining interfaces in the flow with gradually varying velocity and density. The 'model' is essentially an extended version of the Taylor-Goldstein equation with an eigenfunction-finding numerical code. With the help of Ms. Heather Deese, a 1998 Woods Hole Summer Student Fellow, I have solved this equation to determine the propagation speeds of the lowest internal gravity waves given the Murray/Johns data. These results were used to assess the hydraulic criticality of the flow at the sill and narrows.

In a related study, the effects of the earth's rotation (which may be important in the Bab al Mandab) on common hydraulic features such as overflows and jumps was carried out. This work is being carried out in collaboration with Drs. Karl Helfrich of Woods Hole and Eric Chassignet of RSMAS and Mr. Allen Kuo of Columbia. Of particular relevance to the Bab al Mandab is the effect of rotation on the structure and location of hydraulic jumps. The approach is based on analytical hydraulic models and on a numerical technique developed by Helfrich which handles rotating jumps and bores.

RESULTS

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According to the both the three-layer model and the continuously stratified model, the (bi-directional) winter monthly mean flow in the Bab al Mandab hovers near the critical speed with respect to both the first and second internal modes. The (tri-directional) summer flow is substantially subcritical. Significantly, tides cause the instantaneous flow to fluctuate between controlled and noncontrolled states in winter and, to a lesser degree, in summer. Contrary to expectations, the most likely control point is the sill rather than the narrows. The hydraulic control with respect to the first internal mode limits the overall exchange rate while the second internal mode is instrumental in determining how much Red Sea Deep Water is drawn up over the sill.

With regard to the work on the effects of rotation, there are a number of very significant findings. First, it appears that hydraulic control of a rotating flow that is largely separated from one of the side-walls of the channel is impossible. Secondly, hydraulic jumps in separated flows look nothing like nonrotating jumps. The former tend to be sideways and cause isopycnal mixing, the latter vertical and cause diapycnal mixing. Rotation may also cause deep fluid approaching a sill to be deflected and re-enter the basin as a boundary current.

IMPACT/APPLICATIONS

The fact that the Hanish sill is the most likely point of hydraulic control has important implications for the understanding of local features such as mixing and stratification. We predict that the deep flow slightly to the south of the sill should have an overflow character (with strong velocities) followed by a turbulent hydraulic jump. These features are hinted at in a longitudinal salinity section constructed by Murray, but further confirmation is needed. The strength of the tides and the fluctuating nature of the flow criticality near the sill suggest the presence of an internal bore such as observed in the Strait of Gibraltar. Space shuttle photos showing sea surface glimmer patterns have failed to show such a feature. However, if rotation is important, the hydraulic jump may have quite a different character than the one that creates the internal bore at Gibraltar. The apparent lack of (or weakness of) hydraulic control during the summer months suggest increased influence of the Indian Ocean during that period and this is perhaps manifested by the intrusion of Gulf of Aden Intermediate Water into the Red Sea that is observed during that period.

TRANSITIONS

The extended version of the Taylor-Goldstein equation and the numerical code developed to solve it is available to anyone who need it. The code should be useful to anyone interested in the hydraulics of sea straits where cross-strait topography might be important and where the ambiguities of layer models need to be avoided.

RELATED PROJECTS

Prof. Massamichi Inoue of LSU is developing a regional numerical model of the Bab al Mandab. We have spoken about overlaps and about the possibility of using our simple models to help interpret the results of his more realistic and much more complicated model.

Drs. Bower, Price, Fratantoni (of Woods Hole) and Johns (of RSMAS) are proposing a Gulf of Aden outflow study to NSF. Such a study would extend the Murray/Johns measurements of the outflow downstream and would give a more complete picture on which to test ideas about the hydraulic character of the flow.

PUBLICATIONS RESULTING FROM THIS STUDY

Pratt, L. J. , W. Johns, S. Murray, and K. Katsumata. Hydraulic Interpretation of direct velocity measurements in the Bab al Mandab. *J. Phys. Oceanogr.* (accepted)

Pratt, L. J. , H. Deese, S. Murray, and W. Johns. Continuous dynamical modes of the Bab al Mandab and their hydraulic interpretation. submitted to *J. Phys. Oceanogr.*

Helfrich, K., A. Kuo and L.J. Pratt. Rossby adjustment in a rotating channel. *J. Fluid. Mech.* (accepted)

Pratt, L.J, K. Helfrich and E. Chassignet. Long's problem in a rotating channel. *J. Fluid. Mech.* (submitted)